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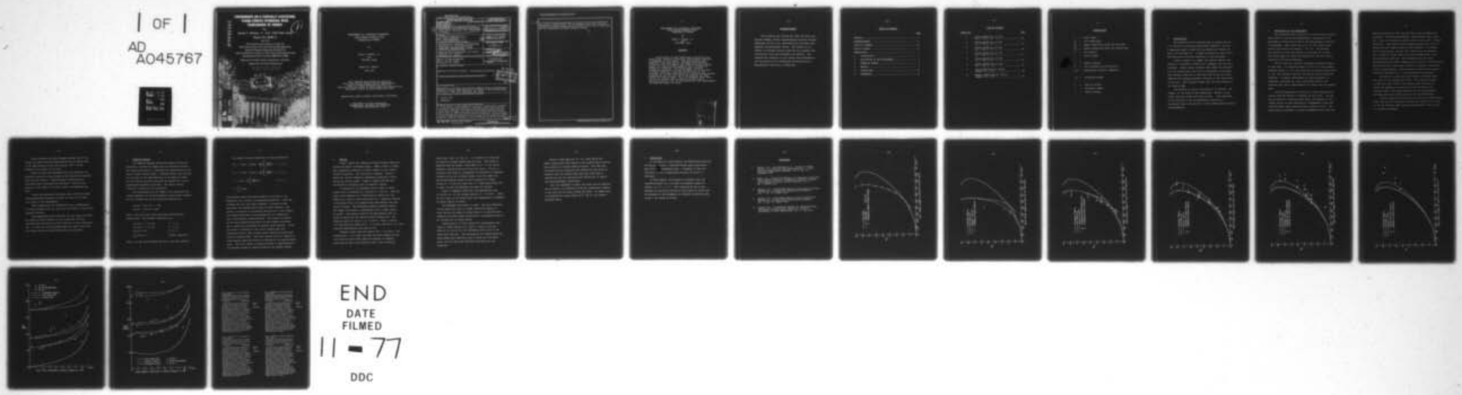

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by

James S. Uhlman, Jr. and Chen-Wen Jiang

Report No. 83481-2

July 1977

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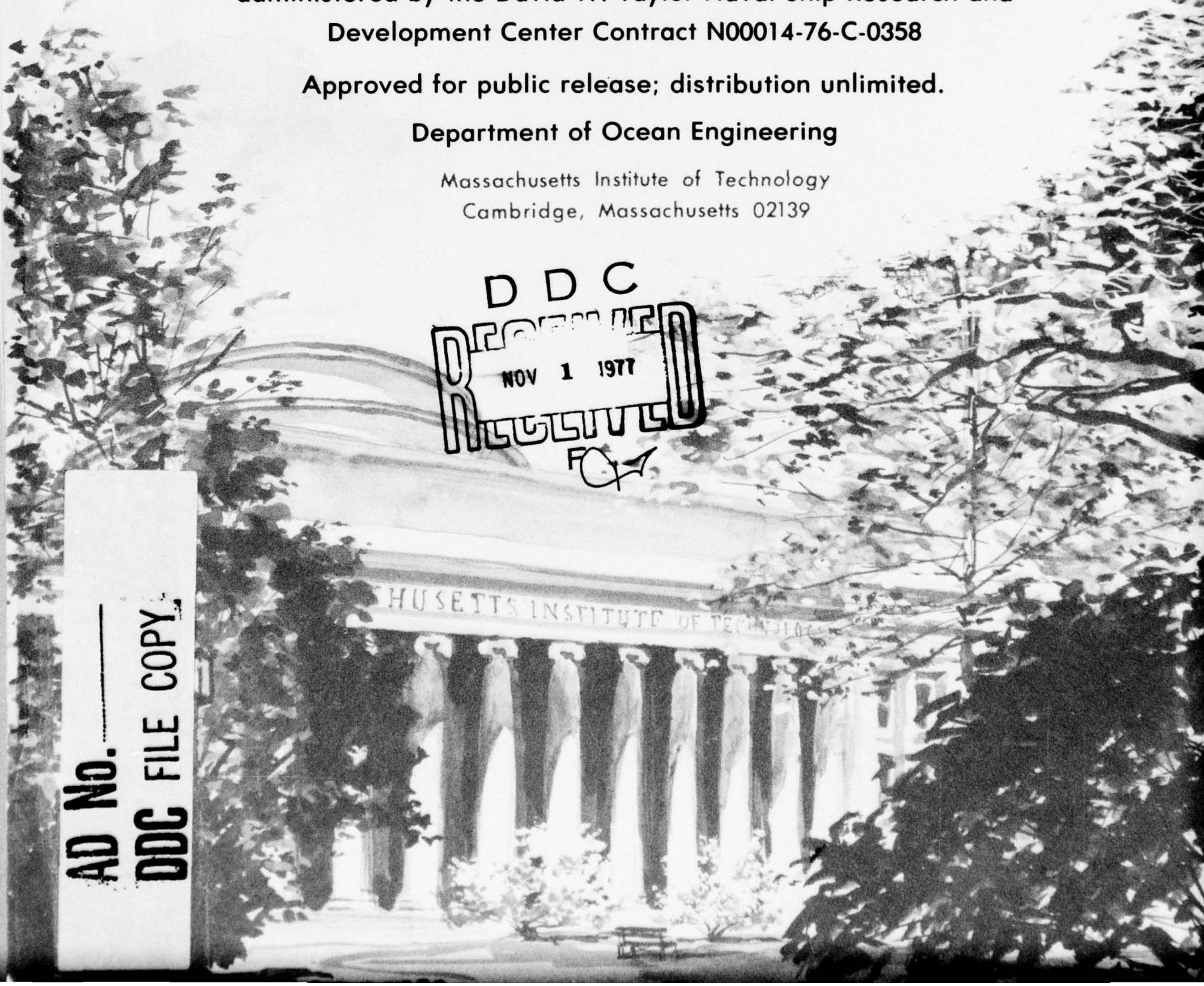

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NOMENCLATURE

c = chord length

C_L = lift coefficient

C_M = moment coefficient about the mid-chord

C_M^* = moment coefficient about the leading edge

f = foil profile

ℓ = cavity length

q = source strength

t = foil thickness at the mid-chord

u,v = perturbation velocity components

x,y = coordinate system

α = angle of attack

σ = cavitation number

γ = vortex strength

1. INTRODUCTION

The objective of this research was to acquire data on a 2-D partially cavitating plano-convex hydrofoil, so that a comparison might be made with the respective theories of Geurst [1] and Wade [2]. A numerical method for small thickness partially cavitating hydrofoil is also developed.

Geurst's theory is a camber line theory, wherein the hydrofoil is assumed to consist of a cambered line with zero thickness. Wade's theory includes both camber and thickness (for the plano-convex case only) by satisfying a flat-plate type boundary condition on the plane side of the foil and a cambered flow tangency boundary condition on the convex side of the foil. Both theories assume that the cavity begins at the leading edge.

The problem of partial cavitation is of interest, for example, in the study of ship propellers. Wherein it may cause transitory loads and severe erosion. Thus knowledge of the accuracy of the two-dimensional theories is a preliminary step in being able to fully understand and control this phenomenon.

2. DESCRIPTION OF THE EXPERIMENTS

The experiments were carried out in the variable pressure water tunnel in the Marine Hydrodynamics Laboratory of the Department of Ocean Engineering at the Massachusetts Institute of Technology. This tunnel has a 20" (51 cm) square cross-section test section of length 3' (92 cm). The maximum flow velocity in the test section is 30 ft/sec (9.1 m/sec). The vacuum pumps can reduce the pressure at the test section centerline to 90 mm Hg absolute.

The foil was a 2-D section connected to mounting plates at both ends. Its dimensions were; 19 3/4" (50.2 cm) between mounting plates, 4" (10.2 cm) chord and a thickness/chord ratio of .06. The pressure side was flat and the suction side was parabolic. To permit measurement of cavity pressures, it contained a pressure tap a few inches down from the top mounting plate and at approximately 17% chord from the leading edge.

The foil was mounted vertically to avoid complications arising from the effects of buoyancy on the cavity. Its top end was fixed to a mounting shaft which led external to the tunnel and was in turn connected to a dynamometer which read pitching moment about mid-chord and a portion of lift. The bottom end was attached to another dynamometer which read the

remaining portion of lift, but was free as far as moment was concerned. The bottom dynamometer, unfortunately, had a load cell in the lift direction rated at 1000 lbs for .006" (.152 mm) deflection. This meant it had inadequate sensitivity for all except the very highest values of lift measured. To correct for this deficiency, the foil lift coefficient was measured over a range of attack angles and tunnel speeds while in the non-cavitating condition. The differences between these measured values and those computed using classical two-dimensional fully wetted foil theory were fitted to a quadratic correction curve by least squares. This correction curve was then used to adjust the measured lift in the cavitated flow condition.

The angle of attack was read through a telescope which was fixed to the top mounting shaft. The telescope viewed a scale which was fixed to the opposite wall and angle of attack was changed by rotating the rigid telescope, top mounting shaft, foil system relative to the top dynamometer and then again fixing this system to the top dynamometer.

Cavity pressure was read (when the cavity was sufficiently long) from the foil pressure tap which was connected to a hole in the top mounting shaft and thus led external to the tunnel to a mercury manometer.

Static pressure was read through pressure tap in the tunnel wall which was positioned mid-way up the tunnel wall at the upstream end of the test section, 24.5" (62 cm) forward of the center of the foil.

Water velocity was determined from the difference in pressure between two taps located in the contraction upstream from the test section. These pressure differences had previously been correlated with different velocities by placing a pitot tube in the test section and compiling the data.

Forces were measured from strain gage indicators which had predetermined conversion factors for each of the load cells used in the dynamometers.

Water temperature was recorded for use in determining the vapor pressure when the cavity was too small to read cavity pressure directly.

The experiments were conducted, for each angle of attack, by reducing tunnel pressure as low as possible and then systematically altering the water velocity to obtain each data set. At each such setting photographs were taken from which the cavity length to chord length ratio was obtained.

3. NUMERICAL METHOD

The computer program written by Golden [5] has been modified to include the camber and foil thickness effects. The steady flow theory is linearized for application to thin foils at small attack angles. Discrete sources and vortices are utilized in the representation of the physical model, and the coupled integral equations are reduced to a set of simultaneous algebraic equations. The cavity closure condition is used in this calculation.

The relationship for the jumps in the tangential and normal components of the perturbation velocity upon crossing the foil surface and cavity projection surface are:

$$u(x,+0) - u(x,-0) = -\gamma(x),$$
$$v(x,+0) - v(x,-0) = q(x),$$

where γ and q are the vortex and source distributions, respectively. The boundary conditions are:

$$v(x,+0) = -\alpha + f'_+(x), \qquad \ell < x \le 1$$
$$v(x,-0) = -\alpha + f'_-(x), \qquad 0 \le x \le 1$$
$$u(x,+0) = -\sigma/2 \qquad 0 \le x \le \ell$$
$$\int_0^\ell q(\xi)d\xi = 0 \qquad \text{closure condition}$$

where ℓ is the cavity length and f(x) is the foil profile.

The coupled integral equations for this problem are:

$$0 = \alpha - f_+'(x) + \frac{1}{2} q(x) + \frac{1}{2\pi} \fint_0^1 \frac{\gamma(\xi)}{x-\xi} d\xi, \quad \ell < x \le 1,$$

$$0 = \alpha - f_-'(x) - \frac{1}{2} q(x) + \frac{1}{2\pi} \fint_0^1 \frac{\gamma(\xi)}{x-\xi} d\xi, \quad 0 \le x \le 1,$$

$$\sigma = -\gamma(x) + \frac{1}{\pi} \fint_0^1 \frac{q(\xi)}{x-\xi} d\xi, \quad 0 \le x < \ell,$$

$$0 = \int_0^1 q(\xi) d\xi.$$

The discrete vortex and source method is utilized in the formulation of a series of simultaneous equations. Upon subdividing the foil into small elements, a discrete vortex and source are located within each of these elements. The vortex is situated on the quarter-chord point of each element, and induced velocities are calculated for all elements at their three-quarter chord positions. The source is located at the three-quarter-chord point and the induced velocities due to source are calculated at quarter chord position. Since the source is singular at the cavity leading edge and termination point, these control points should be placed away from the singularities. The first control point is located at three-quarter chord and source is situated on the quarter chord point. The local vortex or source strength is approximated by the discrete vortex or source divided by the element length.

4. RESULTS

Figure 1 shows the comparison between present numerical results and Wade's thickness theory. Wade's theory is based upon assumptions identical to those leading to the coupled integral equations. His solution is, however, analytic except for certain numerical quadratures required in determining the cavity length. Figure 1 simply confirms that two methods of solution lead to identical results.

In Figures 2-6 the measured cavity length to chord length ratio is plotted as a function of α and α/σ. The flat plate curve referred to is from Geurst's theory [3], the camber line curve is also from Geurst [1]. Numerical results of thickness theory are compared with experimental data and Geurst's theory. The difference between thickness theory and camber line theory is perceptible only at small angles of attack. The general trend of the experimental data is found to agree with the results found by Geurst [1]. For moderate angles of attack, i.e. 4° and 6°, (Figs. 3 and 4), both theories work rather well. It is seen that for $\alpha = 2°$, both theories underestimate the value of ℓ/c.

Figures 5 and 6 show the results for $\alpha = 8°$ and $\alpha = 10°$ respectively. It is seen that here the data diverge so that even the flat plate theory does not predict it properly. This could be due to two effects; first, that, as Meijer

noted also, [Ref. 4], for $\ell/c > .75$ instability occurs and the theory no longer agrees with the data. This might be expected from the theory, since above $\ell/c \approx .75$ the theory predicts a second value of ℓ/c for any given α and α/σ; a situation that might be interpreted as indicative of possible instability for one of these values; here the higher one. The second possible cause of this divergence at higher values of α is the fact that this is a linearized theory and at high α we may be exceeding its range of validity.

Figure 7 compares theoretical and experimental data for $C_L/2\pi\alpha$ vs. ℓ/c for attack angles of 2°, 4° and 6°. Again we see a hint of the trend toward less dependence on thickness at higher angles of attack.

The agreement with theory is good. The only exceptions to this being for high ℓ/c, where instability begins to occur and for low angle of attack where it is possible that midchord cavitation might be occurring, a phenomenon which is not allowed for in either theory.

Unfortunately, no fully wetted foil measurements were taken at attack angles of 8° and 10°, hence it was not possible to correct for the inadequate sensitivity of the lower lift load cell. The uncorrected lift coefficients for these angles were generally near or below the flat plate curve, but the data were unreliable and hence are not presented.

Figure 8 shows $C_M^*/(\pi\alpha/2)$ vs. ℓ/c, where C_M^* is the moment coefficient with respect to the leading edge, positive when tending to increase angle of attack. This data was corrected by first acquiring the location of the center of pressure from the original data and then using that in conjunction with the corrected lift coefficient to obtain the corrected moment coefficient.

Again the agreement is good, but since the two theories are so close it is difficult to see any appreciable tendency in the data for one theory versus the other. No moment data is presented for attack angles of 8° and 10° for reasons discussed above.

5. CONCLUSIONS

In the case of a plano-convex, two-dimensional partially cavitating hydrofoil, linearized theory gives good agreement with the experimental data. A tendency is seen for thickness to gain in importance as angle of attack is decreased.

It would appear, from Figures 2 through 6 that the linearized theory is at its best for moderate angles of attack, i.e. $4° < \alpha < 6°$. This result may be due to the presence of non-linear effects of high angles of attack and the presence of the phenomenon of midchord cavitation which occurs a low angles of attack.

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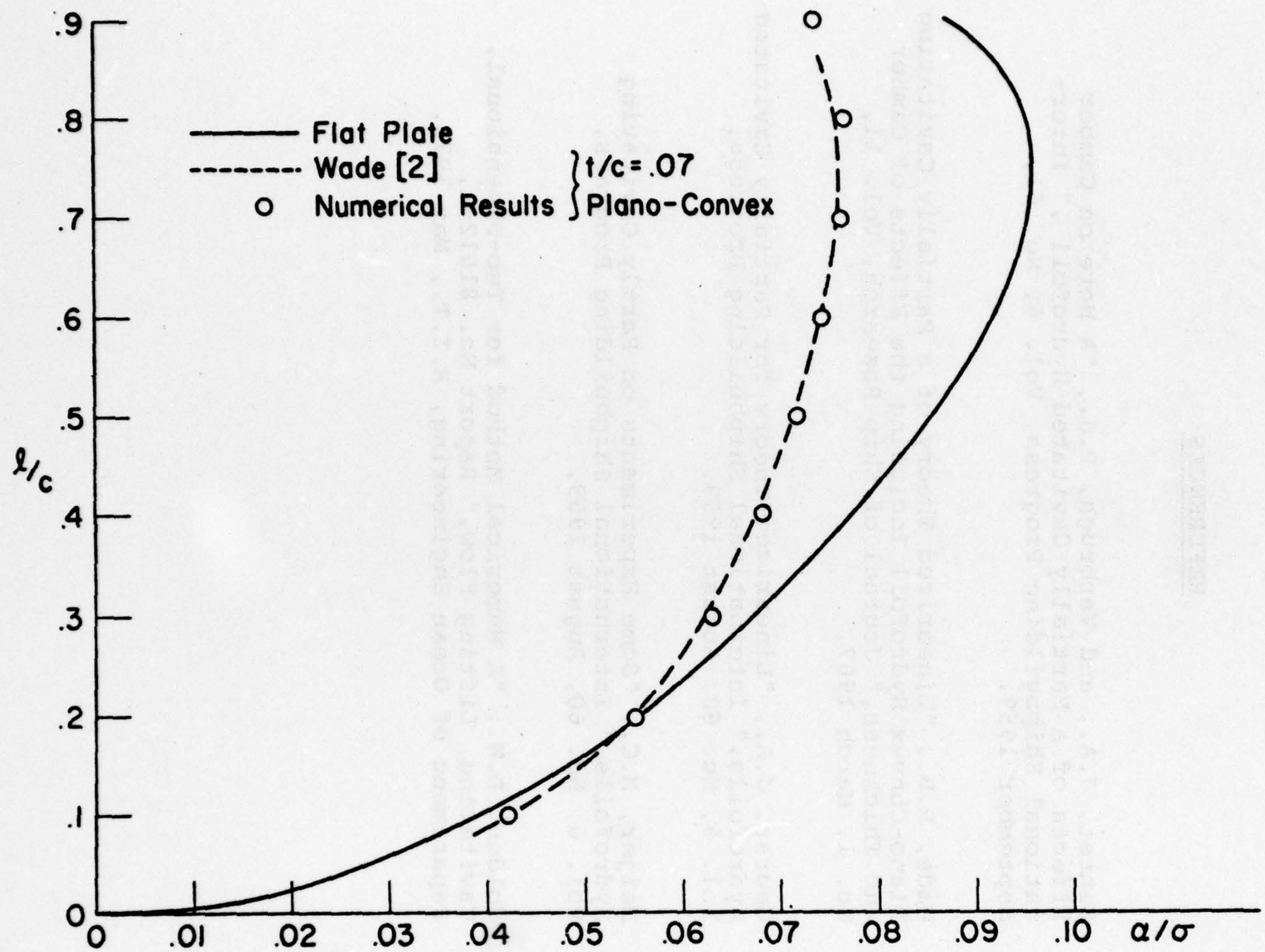

Fig. I Cavity Length vs. α/σ for $t/c = .07$, $\alpha = 4°$

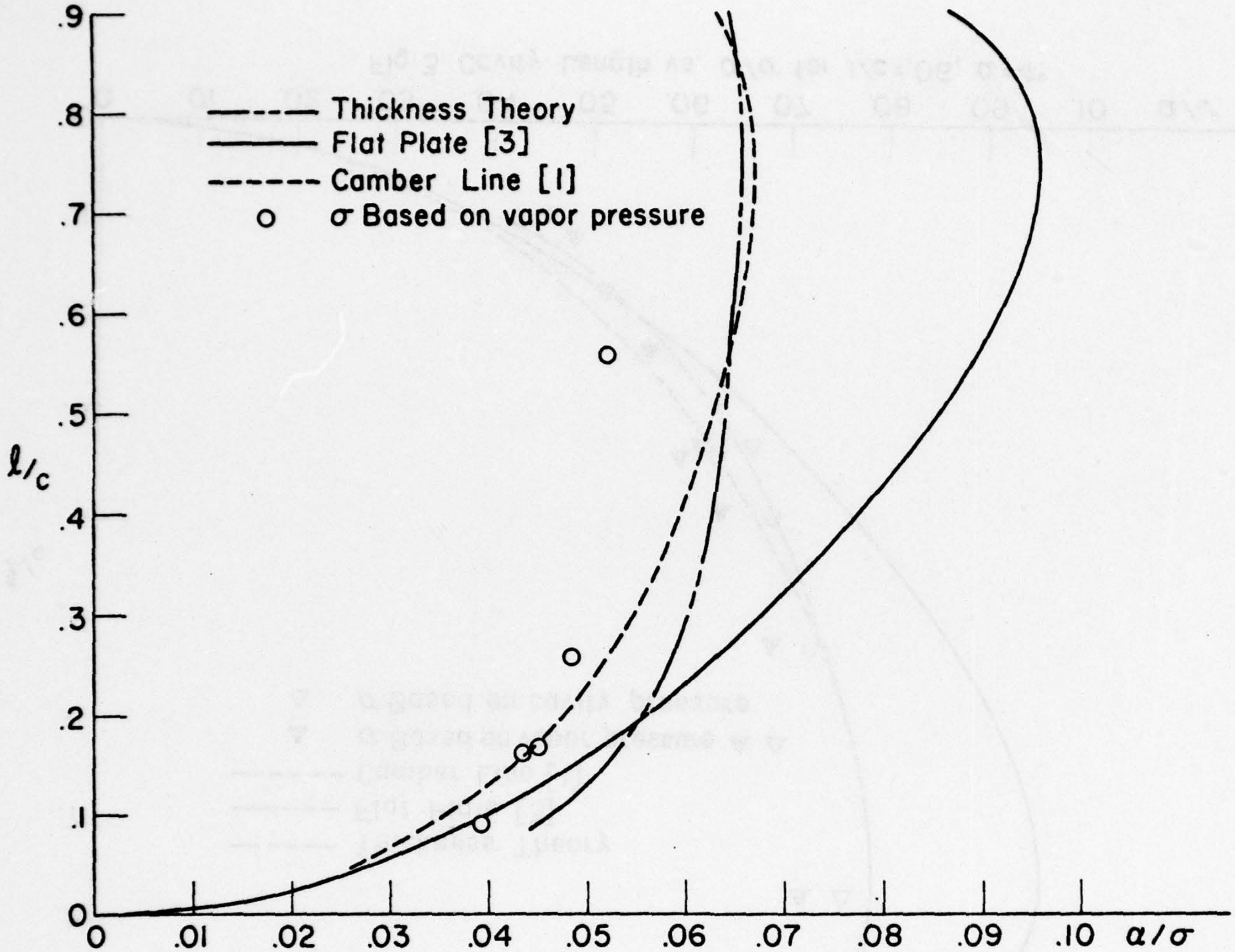

Fig. 2 Cavity Length vs. α/σ for $t/c = .06$, $\alpha = 2°$

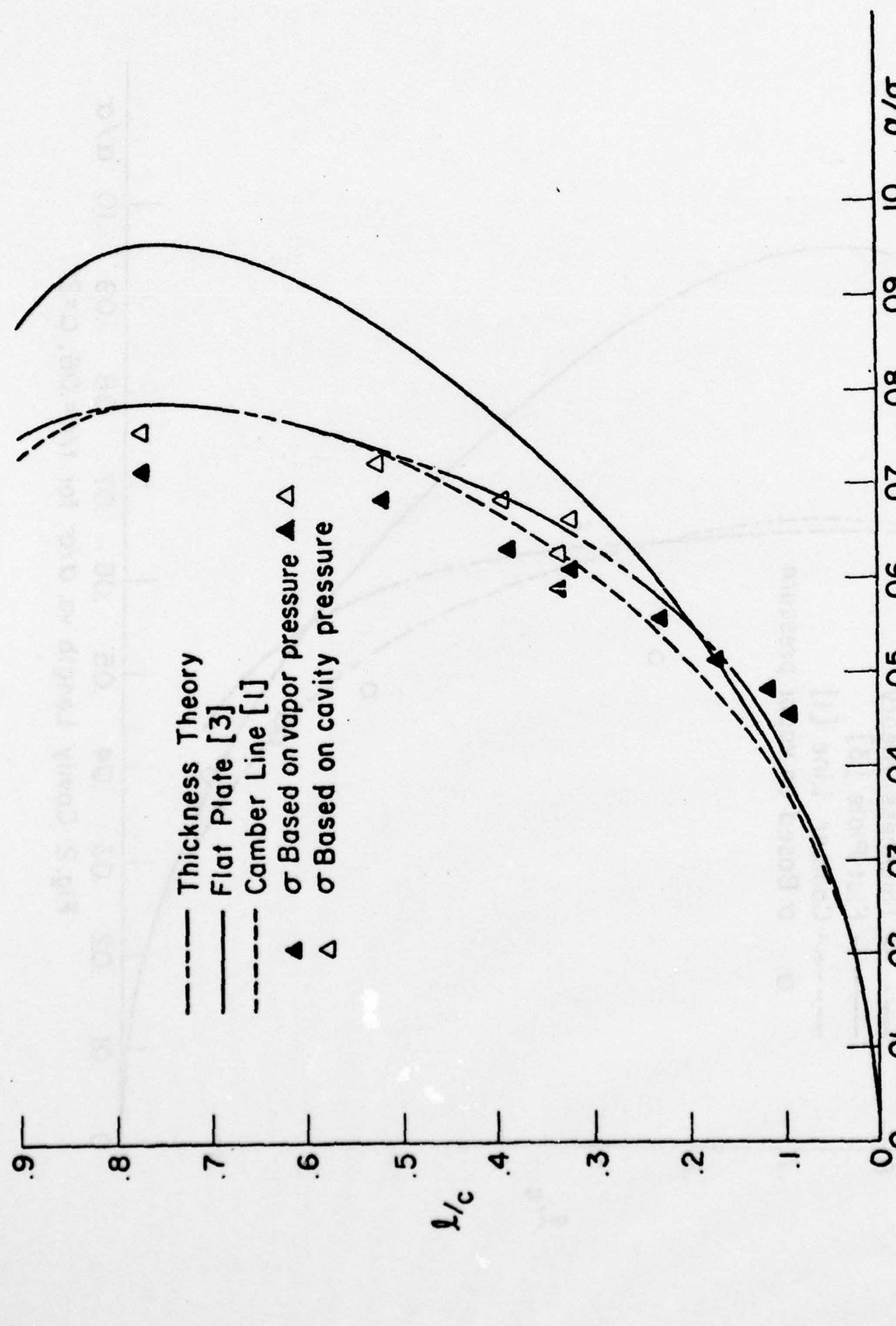

Fig. 3 Cavity Length vs. a/σ for t/c=.06, a=4°

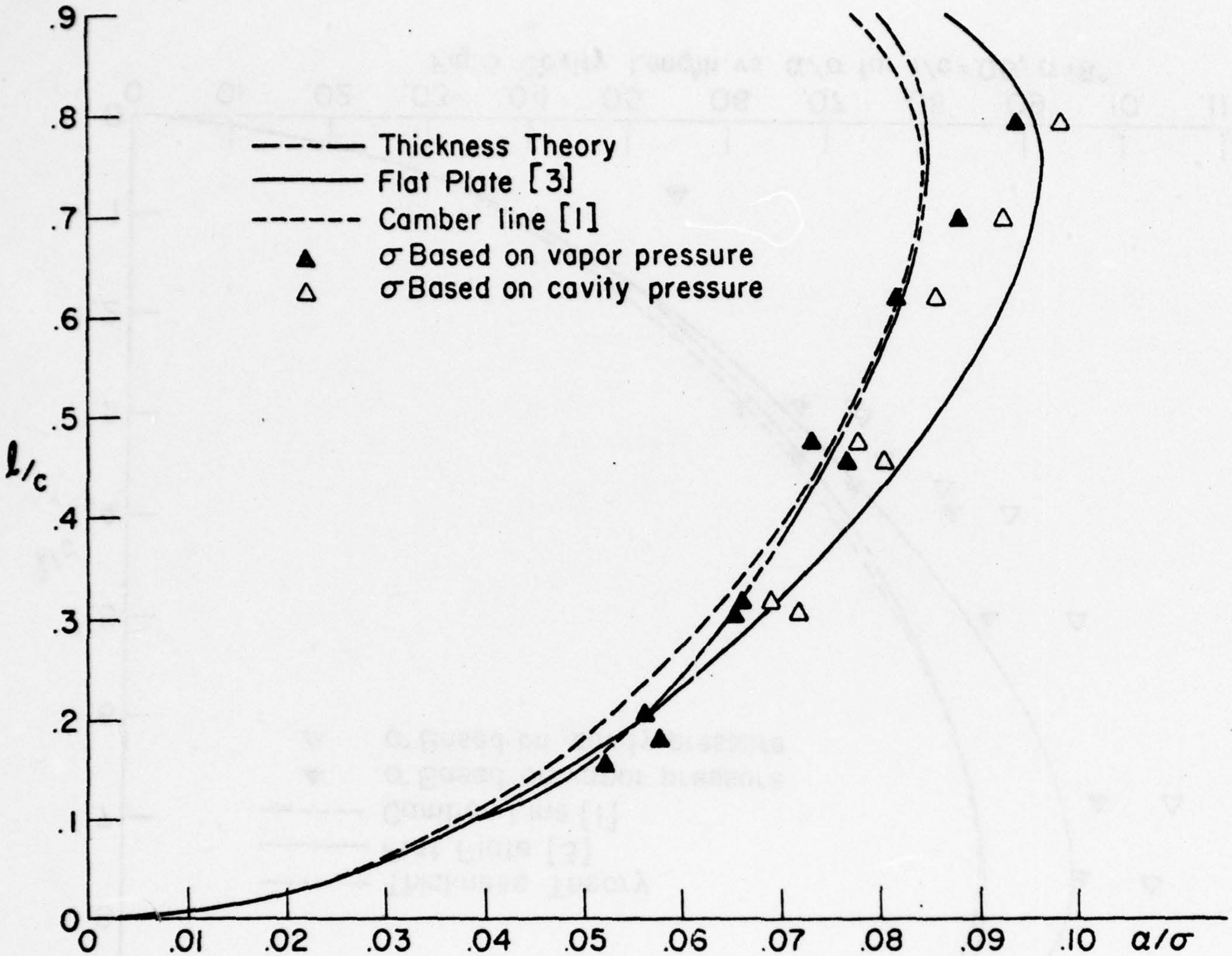

Fig. 4 Cavity Length vs. α/σ for $t/c = .06$, $\alpha = 6°$

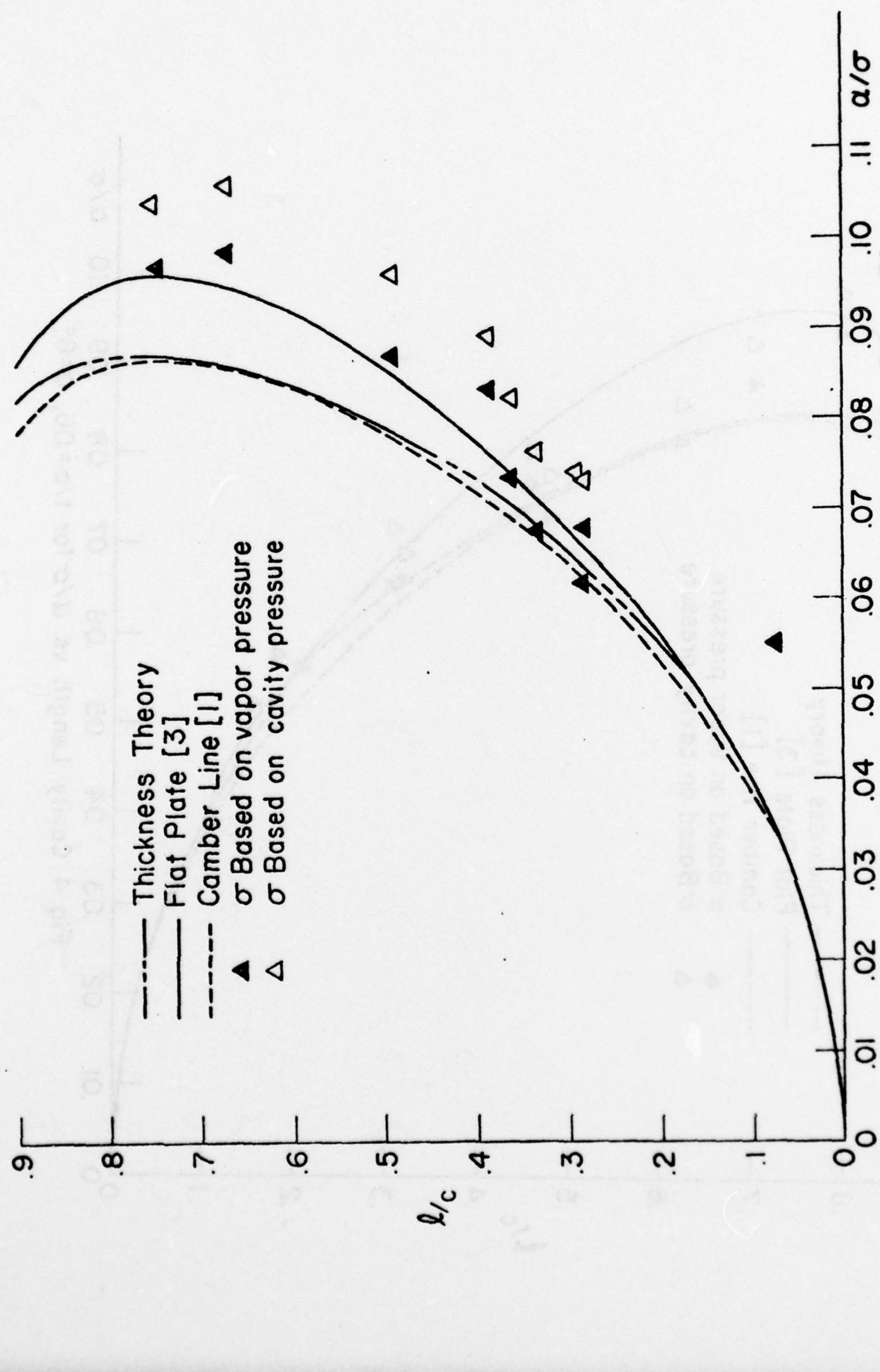

Fig.5 Cavity Length vs. α/σ for $t/c=.06$, $\alpha=8°$

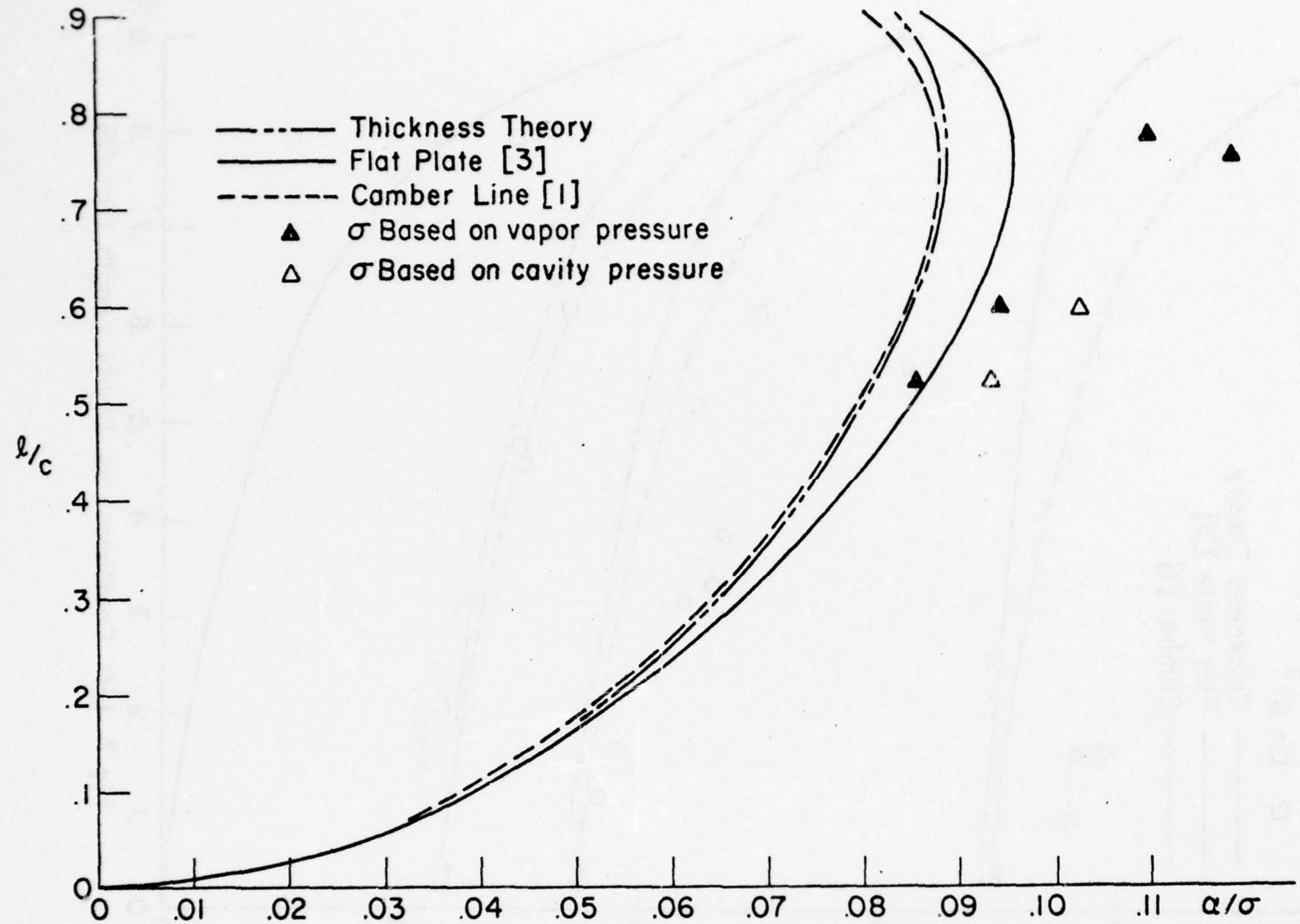

Fig.6 Cavity Length vs. α/σ for $t/c = .06$, $\alpha = 10°$

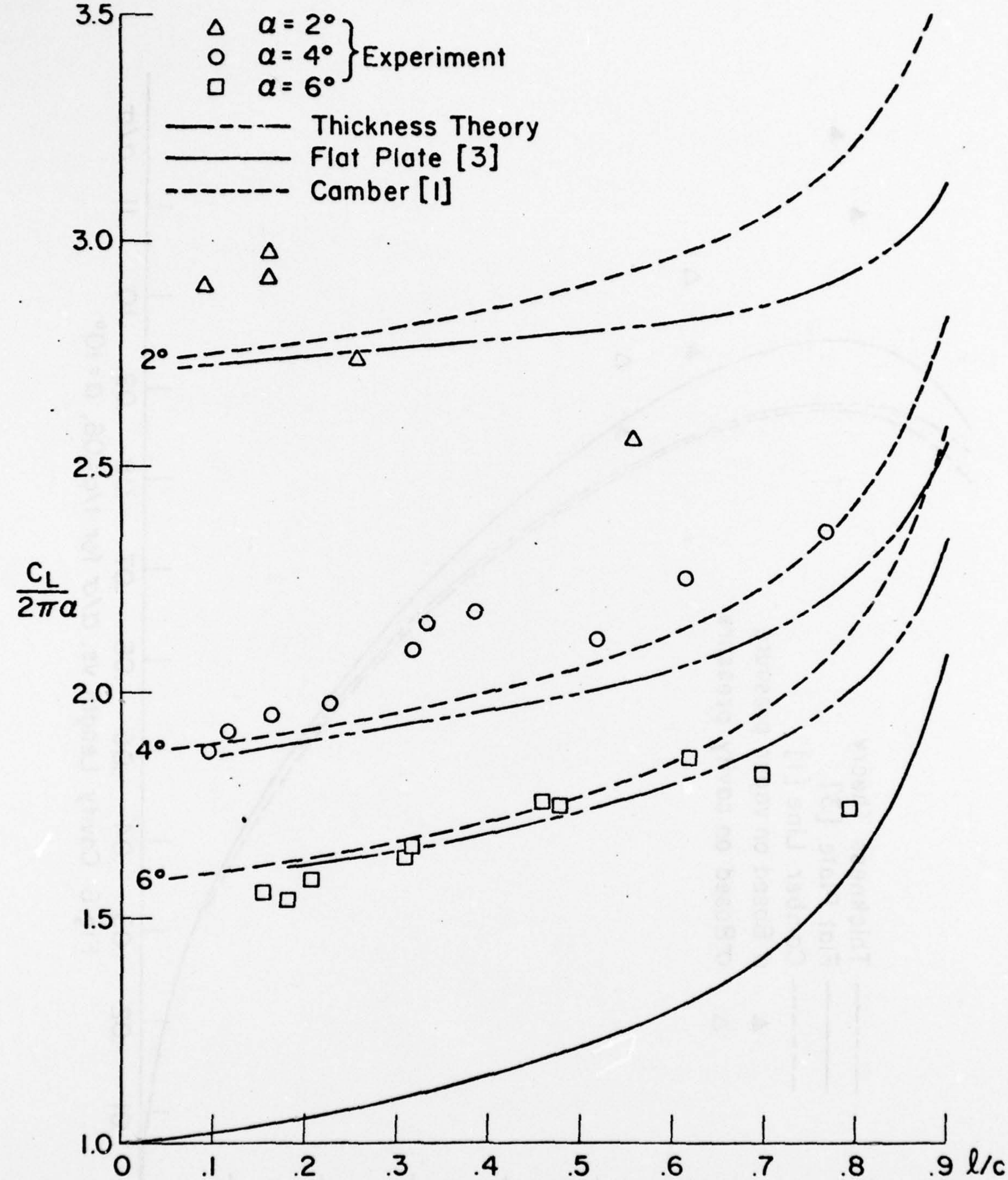

Fig. 7 Lift Coefficient vs. Cavity Length, t/c = .06

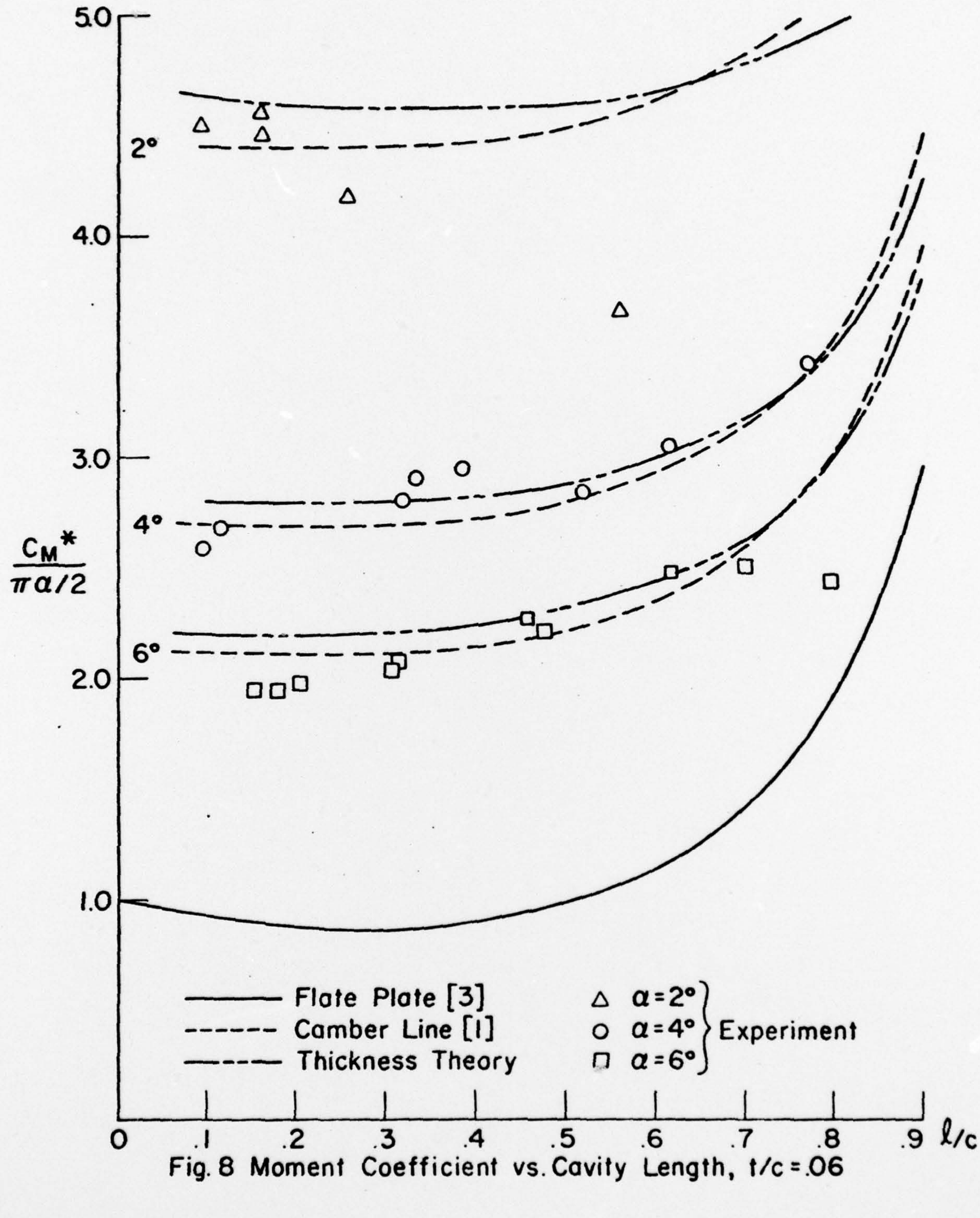

Fig. 8 Moment Coefficient vs. Cavity Length, t/c = .06

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